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THE JPL TELEROBOT OPERATOR CONTROL STATION - OPERATIONAL EXPERIENCES

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ABSTRACT

The Operator Control Station of the JPL/NASA Telerobot Demonstration System provides an efficient man-machine interface for the performance of telerobot tasks. Its hardware and software have been designed with high flexibility. It provides a feedback-rich interactive environment in which the Operator performs teleoperation tasks, robotic tasks, and telerobotic tasks at ease. This paper discusses the to-date operational experiences of this system, particularly related to the 'Object Designate' Process and the Voice Input/Output Process.

INTRODUCTION

The Operator Control Station (OCS) of the JPL/NASA (Jet Propulsion Laboratory / National Aeronautics and Space Administration) Telerobot Demonstration System provides the man-machine interface between the Operator and the System. It provides all the hardware and software for accepting human input for the direct and indirect (supervised) manipulation of the robot arms and tools for task execution. Hardware and software are also provided for the display and feedback of information and control data for the Operator's consumption and interaction with the task being executed. It is a large system, complex yet designed for user-friendliness.

Operational modes of the Telerobot Demonstration System include teleoperated control mode, autonomous robotic control mode, and telerobotic control mode which is a combination of the two former modes and takes the form of traded/shared control (also known as supervisory control). The execution of tasks in these various modes are all exercised from the Operator Control Station.

The OCS contains state-of-the-art mechanical and computing hardware for providing control input to the System. It contains control software and human operator interface software for real-time and user-friendly interaction. Video displays for text, graphics and camera images are provided for operator consumption. Voice input/output is provided to reduce operator work-load. Data manipulation such as 'Object Designate' capability is provided for efficient task definition and instantiation. Access to all Telerobot subsystems is provided for on-line control, monitoring, and off-line software development.

This OCS has been installed and is operational in the JPL Telerobot Testbed since April 1989. As a stand-alone system, it has offered many rewarding and satisfying hours of operational experiences in the man-machine interface, particularly in the utility of the new "object designate" technology, and in the voice input/output process. This paper will discuss these two design elements and operational aspects in detail.

OCS DESIGN REQUIREMENTS

As part of the JPL Telerobot Demonstration System, the OCS acts as the center of action for the System, and necessarily interfaces with all the other subsystems. While referring all discussions on the overall System architecture to references [1,2,3], it suffices to say that OCS interfaces with the Task Planner & Reasoning Subsystem (TPR), Run-Time Control Subsystem (RTC), Manipulator Control and Mechanization Subsystem (MCM), and the Sensing & Perception Subsystem (S&P).

The OCS is configured for two operators, the Primary Operator and the Secondary Operator (also known as the Test Conductor). The primary station of the OCS has all the controls necessary for the Primary Operator to perform all functions independent of the secondary station. And the secondary station has a subset of the capabilities at the primary station, required for monitoring and secondary control purposes. The Operators' functions include the following:

- System management functions: system startup/shutdown, setup, software configuration, other monitoring and diagnostics functions;
- System operation functions: mode transitions, setting system parameters, system calibration, video switching, emergency halt (and other modes of halting), object data manipulation;
- Manual teleoperation functions: hand motions for input to hand controllers, setting subsystem parameters, establishing telepresence via visual, kinesthetic and proprioceptive feedback;
- Autonomous robotic functions: to instantiate, monitor, supervise, direct, confirm and give permission to proceed all actions generated under autonomous planning and control;
- Telerobotic functions: to execute hybrid commands of manual and autonomous control, and transitioning between various degrees of manual and autonomous controls.
- Initiating and executing data logging functions for off-line analysis and system performance evaluation.

Further details of the OCS requirements can be found in [4]. Hardware and software design details are also documented in [5,6].

OCS HARDWARE/SOFTWARE CONFIGURATION

Figure 1 shows the OCS, as implemented at the JPL Telerobot Testbed. The Primary Operator is shown working in conjunction with the Secondary Operator in front of their respective stations. Figure 2 shows the Primary Operator looking into the robot work site area. Direct viewing of the work site is available at the JPL Testbed; and it can also be screened off so that only indirect viewing is available.

For the input of hand motions in manual telerobotic operations, the primary station houses the right and left Force Reflecting Hand Controllers and their electronics. Three overhead video monitors normally show the wing and overhead camera overviews of the task space. Two middle video monitors display special graphics required for the telerobot operations, e.g. force-torque graphics from the robot arms and hands; simulated graphics for time-delay and predicted motions; etc. Directly in front of the Primary Operator are the stereo displays, necessary for the Operator to perform dexterous close-up operations.

The primary station has three input media for command inputs into the OCS primary computer. Keyboard direct commands and system operations are provided for 'hands-off' operations, when the Operator is not using the hand controllers. A 4-tier menu input is provided for normal telerobot task operations. The same menu input commands are also duplicated by voice input, which is implemented with a flexible grammar and recognized as continuous speech commands. Iconic and hierarchical displays are also provided to the Primary Operator for the issuance of task level commands.

The secondary station has a simpler design because of its secondary requirements. It houses two video monitors and the OCS secondary computer. While the Secondary Operator does not have any voice input capability, he can always enter all the commands via the OCS secondary computer terminal, via direct command inputs using the keyboard or via the menu selection process, displayed to him on the OCS secondary computer monitor. Here, the Secondary Operator cannot provide teleoperation hand controller inputs because of the lack of the input devices. All graphics, overlays and video images can be displayed to his two monitors, as routed by an OCS process of video switching.

Common to both stations are the video switcher, which is configured to route any channels (16 input channels of RGB color) to any combination of monitors or input devices (16 output channels). E.g. single camera views can be switched to desired monitors; multi-view can be fed and mixed in a video mixer; single-view video can be fed into a graphics machine for overlaying and mixing graphics on video images. For the "object designate" process, the latter mixing is done through special graphic overlay machines routed through the video switcher.

Other audio mixing, amplification, video encoding and decoding, recording equipments are also implemented in the OCS. A voice synthesizer is installed in conjunction with the voice recognizer. Voice annunciation is used for acknowledgement of command inputs and for the annunciation of certain messages, particularly critical messages. Additionally, both stations have their own individual emergency kill button, which can also be used for a special halt-retract function. Remote power on-off for the robot controllers are provided, and local power monitoring to the OCS racks are also installed.

The OCS computer is configured by a SUN 3/160 workstation as the primary computer, and with a SUN 3/60 workstation as the secondary computer. Both of them are connected to the ethernet for communication with the other subsystems of the Telerobot Demonstrator System. Network communication is considered more than adequate because of the low-bandwidth data rate between the OCS and the other subsystems. The multi-tasking and multi-view window capabilities on the Sun workstation are fully utilized for input and output purposes, as well as to provide terminal emulation communication to all Telerobot subsystems and users.

OCS software consists of multiple processes performing the following functions:

- Command Processing: OCS-specific commands and task level commands
- Message Processing and Display
- Ethernet and External Subsystem Interface
- Video Switch Operation and Control
- Wire Frame Object Designation
- Voice Input/Output Processing

While explanations on all these processes have been given in [6], the following discusses the last two processes in more detail.

OBJECT DESIGNATION PROCESS

This process permits the Operator to interactively update the position and orientation data of known objects by a mouse point-and-designate sequence. By so doing, any discrepancy, error, or unintentional displacement of objects - as represented in the initial data base - can by reconciled.

Task situation

Figure 3 shows the Telerobot Testbed robot work site. Two ORU (orbit replaceable unit) modules are shown sitting on the "stowbin", which is a raised and tilted rack with the appropriate SIC's (Standard Interface Connector, a standard Polar Platform design, which permits mechanical and electrical mating and coupling). The module to the right, which has a cubical shape, is better known as the electronics module; and the module to the left is the science instrument. These modules and the rack designs simulate existing designs. The SIC is a true copy of the current design (as of mid-1988).

One of the telerobot tasks to be performed at the Telerobot Testbed is to remove the electronics module from a "baseplate" location, which is shown situated between the bases of the two manipulator robots. After removal from the baseplate location (single-arm as well as dual-arm), it will be inserted into the stowbin SIC adapter.

This type of module removal, maneuver and insertion task scenario is to be performed by manual teleoperation, or by supervised telerobot control using compliant force-position control. For the latter, autonomous robot motion is commanded via 'macro' commands. And since autonomous motions are involved, 'accurate' data bases are necessary. The degree of accuracy required for the autonomous fine motions has been bounded at 5 millimeters, such that the chamfer and compliant control will permit the final correct seating.

When the stowbin or rack does not have an absolute calibrated data base entry with the degree of accuracy just stated, the technique of 'object designation' has to be invoked.

The designation process

The 'object designation' is initiated by having the following data sent to OCS: (a) object model; (b) object homogeneous transform; (c) camera models.

The object model is a wireframe description, basically consisting of a list of vertices of the object, and a list of the edges of the object. The list of vertices is accompanied by the positions of the vertices relative to a local coordinate system. The homogeneous transform of this local coordinate system origin defines the object's location and orientation, as currently stored in the data base. A bounding box can be computed from the above data points, and the box will be used in subsequent viewing manipulations. Lastly, the geometric models of the cameras (five cameras in the current Testbed setup) are sent to the OCS; these models define the 2-dimensional coordinates on the camera focal plane when given the x-y-z location of a point in the work space.

Now the OCS is ready for the actual designation process. Up to two camera views can be selected; the two views are constrained by the two units of graphic overlay hardware in this current installation. Upon each monitor (camera view) selection, the overlaid video scene is presented on the monitor.

At the top of the monitor screen are the fourteen menu choices (to be discussed later). If indeed the wire frame of the object fits into the work space as seen by the camera's field of view, the wire frame model will appear on the screen. Otherwise, a message will appear saying that the object is out of view. In that case, the Operator can choose a 'conjure' action, forcing the presentation of the object model into the workspace. Figure 4a shows such a conjured view of the electronics module wire frame. The actual module is also visible on the right side of the video screen. Also notice the solid and dotted edges of the wire frame, providing a pseudo 3-dimensional perspective. This view is from a right wing camera.

If the module is not in a good perspective or viewing angle, certain rotations can be done to this model. The menu item at the top of screen, including 'left', 'right', 'top', 'bottom', 'rotate front' can be activated to show different views of the model.

At this point, a point selection sequence can be performed to associate vertices of the wire frame model to the vertices of the object as seen on the screen. A user-friendly clicking process has been designed into this OCS software. Figure 4b shows the state where 1 vertex has been associated (notice the circle pair surrounding the right vertex on the top face), and a second vertex is being designated (notice the 'rubber-band' cursor).

After selection of a few points on an individual screen, the point-fitting action can be activated that will exercise a least squares algorithm to fit the selected vertices to the designated locations. A minimum of three points will provide translational and rotational fitting. Any less number of points will be fitted with a translational fit only. Figure 4c shows the fitted wire frame model after three points were selected.

Usually, a single-camera-view fit will not provide a very good fit, because of the lack of 'depth'. Figure 4d illustrates the point. This is a view from a left wing camera, looking at the same fitted wire frame of Figure 4c. Even though the fit looks good in the right camera view, the need for improvement in the left camera view is evident. Normally, an orthogonal view will serve the purpose well, as in this second view. Figure 4e shows the results on the left view when an extra point, i.e a total of four points, is selected and fitted. The fit looks perfect, and so does the fit viewed from the right camera, shown in Figure 4f. After the fit, the root-mean-square error is always displayed to the Operator, on screen and by voice.

The object designation process can now be terminated by either activating 'complete' or 'cancel'. In the former, the new object location and orientation will be returned to the data base for updating.

Experiences have shown that root-mean-square errors of 1.5 pixels or less can easily be obtained consistently upon the fitting of six vertices. Six to eight vertices are normally more than enough to define an object. For shallow objects, it is not always possible to pick even that many vertices. This kind of pixel accuracy translates directly into location accuracy. Depending on the focal length and zoom of the camera, and on the accuracies of the camera models, accuracies up to 5 millimeters are attainable. For cases when such accuracies are not attained because of different sources of errors, another technique need to be invoked, namely 'relative update' technique [1].

VOICE INPUT/OUTPUT PROCESSING

The OCS has been installed with a continuous speech recognition system, the VERBEX Series 5000 system (which has its own simple voice synthesis module), and a voice synthesis system, the DECtalk DTC01 system. A custom set of vocabulary and grammar has been designed and implemented with the VERBEX system, specially designed for the OCS telerobotic operations. Standard English sentences in the form of ASCII text strings are sent to the DECtalk for voice annunciation; and where necessary, specific phonemic phrases are sent so as to produce more natural sounding voiced messages.

Voice input

The vocabulary and grammar set was developed according to the needs of the Operator during his operation of a typical telerobotic sequence. Essentially, this set duplicates all the keyboard or menu inputs to all the processes in the OCS software on the SUN 3/160 Primary Workstation. This set is written on the SUN workstation as a text file, called a grammar file or grammar-definition file. Using a VERBEX supplied software (for the SUN development environment), this text file is converted into a binary, machine readable recognizer file. The latter is transferred (i.e. downloaded) to the resident RAM memory and/or data cartridge in the VERBEX unit.

For the Operator to use the voice recognition system, his voice has to be trained and stored as templates on a voice file. The VERBEX supplies a user friendly development facilities for the Operator to first 'enroll' the new words in the vocabulary set, and then to train on possible combinations of phrases permissible by the grammar. Typically, a session of training for this OCS Telerobot vocabulary/grammar set is 90 minutes. Experience has shown that three training sessions normally produce very reliable voice files, where recognition accuracy and rejection accuracy could be well above 95%.

A set of 120 vocabulary words has been designed for the current OCS Telerobot operation scenarios. These words are single words as well as compound words, strung together as they are continuously spoken. Examples are: activate, cancel, clear, command_confirm, the_upper_left_display, the_stereo_cameras.

Simple grammars are designed into the use of these vocabulary words. They consist of single word commands, noun or noun phrases, and prepositions/connectors. Examples of the single word commands are: initiate, select, switch, set_video_switch_defaults, command_confirm, activate, move, verbex_report (an escape command). Examples of the noun or noun phrases are: display, camera, the_upper_right_display, the_left_wing_camera, object_designate_mode, tool_mode. Examples of the prepositions and connectors are: switch camera alpha to display charlie using channel 2.

For the two reasons of (a) that all vocabulary words are not used in one single telerobot session or operation sequence, and (b) that recognition accuracy can further be improved, the set of vocabulary words are grouped into six groups. These six groups are also consistent with the modes of telerobot operation:

- o Host mode
- o Video switch mode
- o Object designate mode
- o Vision arm manipulate mode
- o Teleoperation mode
- o Telerobot mode.

When one of these six modes are selected, a help file is also displayed on the OCS console beside the command and message windows. Figures 5(a)-5(f) show the OCS monitor displayed with the voice_command help file on the left window, during the above stated six modes. The complete voice vocabulary and grammars are listed in the help windows. (All the possible combinations can be derived from the lists, but obviously not enumerated in the window.) Shown also in the figures are the command window, normal message window and critical message window. The menu selections are also highlighted.

Voice output

In terms of voice synthesis, no special effort is needed for custom designing the voices or designing the phrases. The DECtalk provides six default voices with default parameters such as rate and pitch; where such parameters can easily be changed in the text string. The text strings sent to DECtalk need not be customized, and can be written in plain English with normal abbreviations and even with certain acronyms. Normal phrasing, with commas and periods, usually produces intelligible human speech. Where necessary to put emphasis on certian words, or where the English pronunciation deviates from standard rules, the phrase or the specific word can be written in special phonemic forms. Such phonemic forms bypass the extensive-yet-still-limited dictionary look-up rules in DECtalk, and will faithfully produce the correct accents and pronunciation so desired by the Operator or dictated by the contents and context of text phrase.

These text phrases, i.e. voice messages, are contained in a 'Message_Definition_File' which is a text file to the OCS software. Thus, the definition of the phrases, including the specific pronunication of the phrases, could be changed at will by the Operator (i.e. user, not necessarily a programmer), without the burden of having to recompile the whole OCS software.

Likewise, since the DECtalk requires as input text files written in ASCII strings, it can be used to annunciate phrases of any language. The only limitation is the roughly 40 phonemes, i.e. basic unit of sounds, of the English language. These phonemes contain all the English vowels, unstressed vowels, dipthongs, syllabic consonants, and consonants.

SUMMARY

The JPL/NASA Telerobot Demonstration System is scheduled for complete system integration and telerobot operation in the Fall of 1989. The Operator Control Station of the System has been developed, installed, operational, and integrated into the System infrastructure. While limited amount of exposure is gained to-date on complete telerobot task executions, the Operator Control Station has offered many rewarding and satisfying hours of operational experience as a stand-alone system.

The man-machine interface has been shown to be effective, particularly in the utility of the new 'object designation' technique. Through this technique, data bases can be effectively updated and the need for absolute data base calibration is greatly reduced. Future evolution of the same technique would also bring about interactive data base construction and better graphics interface to the Operator. The voice input and output system is not just a showy convenience, but is proven to be an indispensible companion to the Operator. Even though his workload is not being reduced by these technical advances, his operational efficiency is greatly enhanced and his hands are freed to do telerobot operations. Further experience with the Telerobot System operation and the man-machine interface operation in the upcoming months will certainly suggest improvements and additions to this Operator Control Station.

Acknowledgements

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Figure 1. JPL/NASA TELEROBOT DEMONSTRATION SYSTEM - Operator Control Station

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Figure 2. OCS Looking into Robot Work Site

Figure 3. Telerobot Testbed - Robot Work Site

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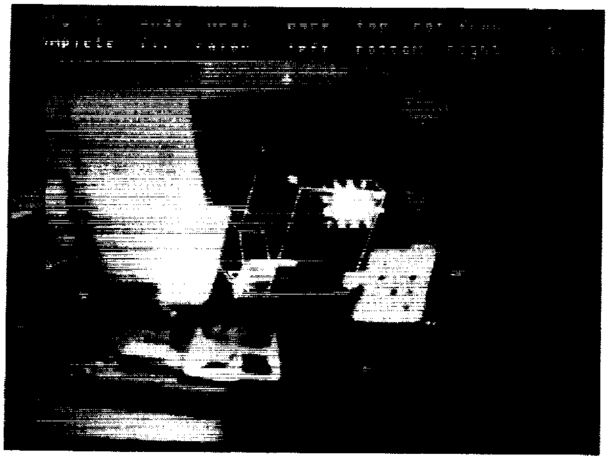
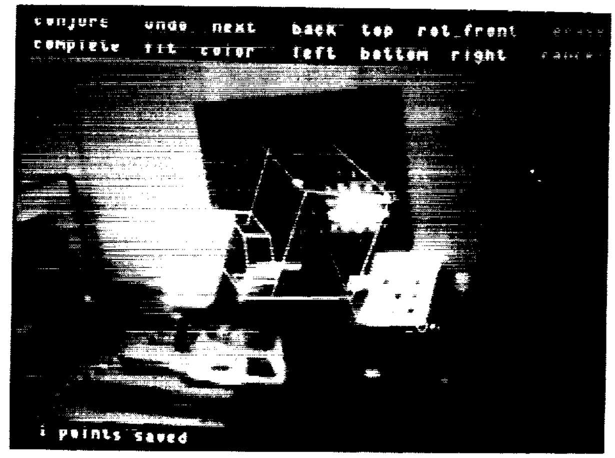
Figure 4. Object Designation Overlaid Camera Views

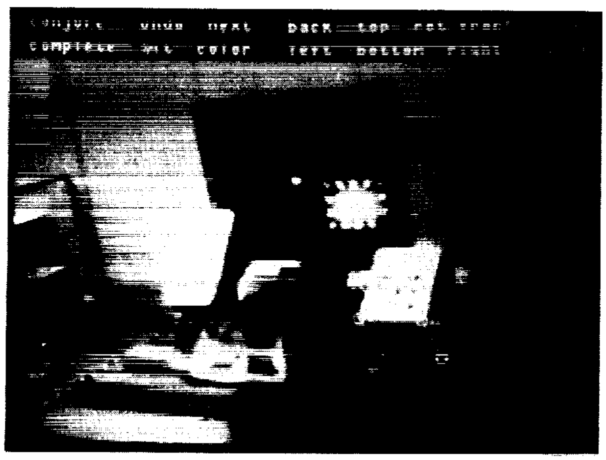
(a) CONJURED OBJECT, RIGHT VIEW



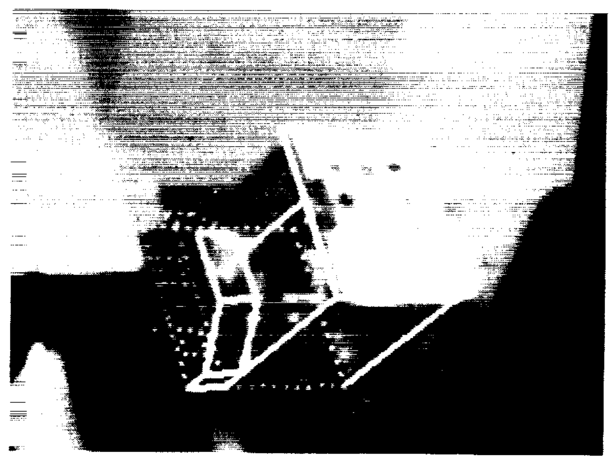
(b) SECOND VERTEX BEING DESIGNATED



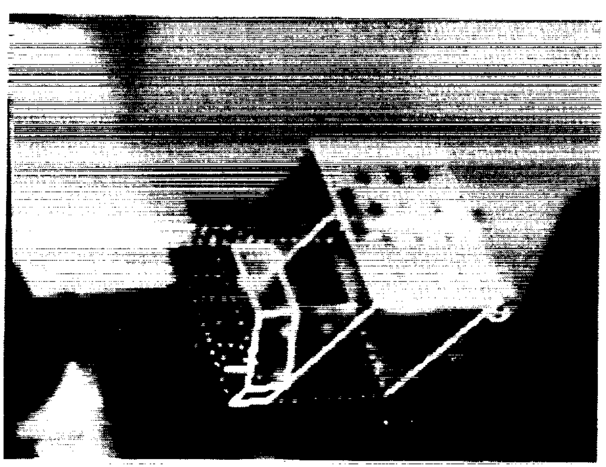
(c) FITTED IMAGE WITH 3 POINTS



(d) LEFT VIEW, USING SAME FIT AS IN (c)



(e) LEFT VIEW, 4-POINT FIT



(f) RIGHT VIEW, 4-POINT FIT

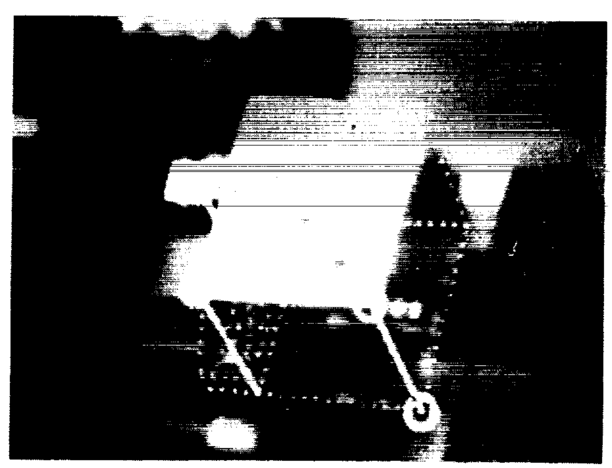


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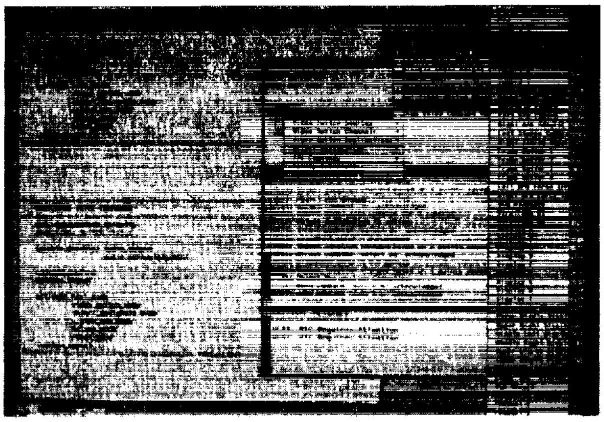
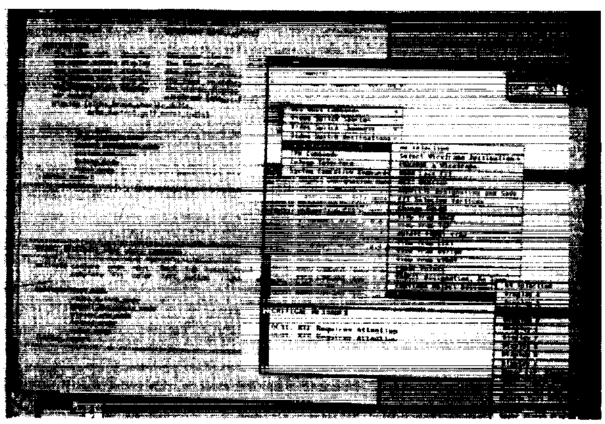
Figure 5. OCS Voice System - Grammar and Vocabulary

(a) HOST MODE

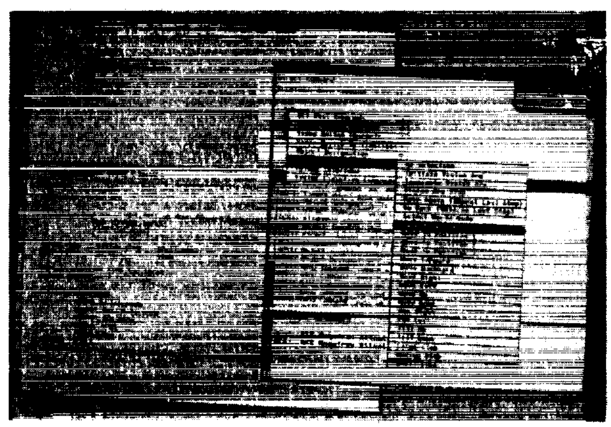


(b) VIDEO SWITCH MODE

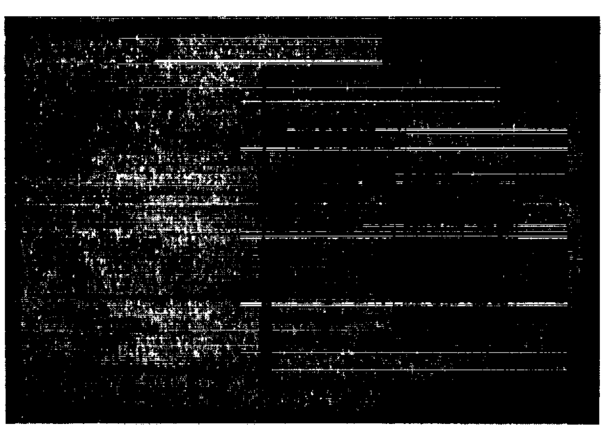
(c) OBJECT DESIGNATE MODE



(d) VISION ARM MODE



(e) TELEOPERATION MODE



(f) TELEROBOT MODE